Grounded Cognition

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Annu. Rev. Psychol. 2008. 59:617–45

First published online as a Review in Advance on August 15, 2007

The *Annual Review of Psychology* is online at http://psych.annualreviews.org

This article's doi:
10.1146/annurev.psych.59.103006.093639

0066-4308/08/0203-0617$20.00

Key Words

cognitive architecture, imagery, representation, simulation, situated action

Abstract

Grounded cognition rejects traditional views that cognition is computation on amodal symbols in a modular system, independent of the brain's modal systems for perception, action, and introspection. Instead, grounded cognition proposes that modal simulations, bodily states, and situated action underlie cognition. Accumulating behavioral and neural evidence supporting this view is reviewed from research on perception, memory, knowledge, language, thought, social cognition, and development. Theories of grounded cognition are also reviewed, as are origins of the area and common misperceptions of it. Theoretical, empirical, and methodological issues are raised whose future treatment is likely to affect the growth and impact of grounded cognition.

Contents

WHAT IS GROUNDED COGNITION?

Standard theories of cognition assume that knowledge resides in a semantic memory system separate from the brain's modal systems for perception (e.g., vision, audition), action (e.g., movement, proprioception), and introspection (e.g., mental states, affect). According to standard theories, representations in modal systems are transduced into amodal symbols that represent knowledge about experience in semantic memory. Once this knowledge exists, it supports the spectrum of cognitive processes from perception to thought.

Conceptions of grounded cognition take many different forms (Gibbs 2006, Wilson 2002). In general, however, they reject the standard view that amodal symbols represent knowledge in semantic memory. From the perspective of grounded cognition, it is unlikely that the brain contains amodal symbols; if it does, they work together with modal representations to create cognition.

Some accounts of grounded cognition focus on roles of the body in cognition, based on widespread findings that bodily states can cause cognitive states and be effects of them (e.g., Barsalou et al. 2003, Lakoff & Johnson 1980, Smith 2005b). Most accounts of grounded cognition, however, focus on the roles of simulation in cognition (e.g., Barsalou 1999, Decety & Grèzes 2006, Goldman 2006). Simulation is the reenactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind. As an experience occurs (e.g., easing into a chair), the brain captures states across the modalities and integrates them with a multimodal representation stored in memory (e.g., how a chair looks and feels, the action of sitting, introspections of comfort and relaxation). Later, when knowledge is needed to represent a category (e.g., chair), multimodal representations captured during experiences with its instances are reactivated to simulate how the brain represented

perception, action, and introspection associated with it.

According to this account, a diverse collection of simulation mechanisms, sharing a common representational system, supports the spectrum of cognitive activities. The presence of simulation mechanisms across diverse cognitive processes suggests that simulation provides a core form of computation in the brain. Mental imagery constitutes the best known case of these simulation mechanisms (e.g., Kosslyn 1980, 1994). Whereas mental imagery typically results from deliberate attempts to construct conscious representations in working memory, other forms of simulation often appear to become active automatically and unconsciously outside working memory.

Still other accounts of grounded cognition focus on situated action, social interaction, and the environment (e.g., Barsalou 2003, Barsalou et al. 2007a, Glenberg 1997, W. Prinz 1997, Rizzolatti & Craighero 2004, Robbins & Aydede 2007, E. Smith & Semin 2004, Yeh & Barsalou 2006). From this perspective, the cognitive system evolved to support action in specific situations, including social interaction. These accounts stress interactions between perception, action, the body, the environment, and other agents, typically during goal achievement.

It is important to note that the phrase "embodied cognition" is often used when referring to this collection of literatures. Problematically, however, "embodied cognition" produces the mistaken assumption that all researchers in this community believe that bodily states are necessary for cognition and that these researchers focus exclusively on bodily states in their investigations. Clearly, however, cognition often proceeds independently of the body, and many researchers address other forms of grounding. "Grounded cognition" reflects the assumption that cognition is typically grounded in multiple ways, including simulations, situated action, and, on occasion, bodily states. Perhaps grounding will one day become such a widely accepted assumption that "grounded" falls away, leaving "cognition" and thereby solving this problem.

Origins of Grounded Cognition

Perhaps surprisingly, grounded cognition has been the dominant view of cognition for most of recorded history. Nearly all prescientific views of the human mind going to back to ancient philosophers (e.g., Epicurus 341–270 B.C.E./1987) assumed that modal representations and imagery represent knowledge (Barsalou 1999, J. Prinz 2002), analogous to current simulation views. Even nativists, such as Kant (1787/1965) and Reid (1785/1969), frequently discussed modal images in knowledge (among other constructs).

In the early twentieth century, behaviorists attacked late nineteenth-century studies of introspection, banishing imagery from much of psychology for not being sufficiently scientific, along with other cognitive constructs (Watson 1913). When cognitive constructs reemerged during the Cognitive Revolution of the mid-twentieth century, imagery was not among them, probably for two reasons. First, the new cognitivists remembered Watson's attacks on imagery and wanted to avoid the same criticisms. Second, they were enthralled with new forms of representation inspired by major developments in logic, linguistics, statistics, and computer science. As a result, theories of knowledge adopted a wide variety of amodal representations, including feature lists, semantic networks, and frames (Barsalou & Hale 1993).

When early findings for mental imagery were reported in the 1960s (for reviews, see Paivio 1971, Shepard & Cooper 1982), the new cognitivists dismissed and discredited them (e.g., Pylyshyn 1973). Nevertheless, the behavioral and neural evidence for imagery eventually became so overwhelming that imagery is now accepted as a basic cognitive mechanism (Kosslyn et al. 2006).

Most recently, research in grounded cognition has challenged theories that originated during the Cognitive Revolution on

numerous grounds (e.g., Barsalou 1999, Glenberg 1997, Harnad 1990, Lakoff 1987, Searle 1980). First, little empirical evidence supports the presence of amodal symbols in cognition. Instead, amodal symbols were adopted largely because they provided elegant and powerful formalisms for representing knowledge, because they captured important intuitions about the symbolic character of cognition, and because they could be implemented in artificial intelligence. Second, traditional theories have been challenged on the grounds that they fail to explain how cognition interfaces with perception and action (the grounding problem). Third, traditional theories increasingly face a lack of understanding about where the brain stores amodal symbols and about how amodal symbols could be consistent with neural principles of computation.

In place of traditional theories, researchers in grounded cognition have turned away from amodal symbols, focusing instead on simulation, situated action, and bodily states. In many respects, these researchers have rediscovered the classic philosophical assumption that modal representations are central to knowledge, reinventing this assumption in the modern contexts of psychology, cognitive science, and neuroscience. As a result, grounded theories focus increasingly on neural representations in the modalities, and less on conscious imagery.

Common Misperceptions of Grounded Cognition

Because modern grounded approaches are so new, we are far from having a unified view. Furthermore, the diverse approaches that exist are not specified computationally or formally. For these reasons, vagueness exists and misperceptions follow.

Grounded theories are often viewed as completely empiricist and therefore inconsistent with nativism. As noted above, however, classic nativists assumed that imagery played central roles in knowledge. Indeed, there are no a priori reasons why simulation cannot have a strong genetic basis. Genetic contributions almost certainly shape the modal systems and memory systems that capture and implement simulations. Some simulations could have a genetic basis.

Grounded theories are often viewed as recording systems that only capture images (e.g., cameras) and are unable to interpret these images conceptually (e.g., Haugland 1991, Pylyshyn 1973). As described below, however, grounded theories are capable of implementing the classic symbolic functions that underlie conceptual interpretation (e.g., Barsalou 1999, 2005a).

Grounded theories are often viewed as only using sensory-motor representations of the external world to represent knowledge. As a result, it is argued that grounded theories cannot represent abstract concepts not grounded externally. Importantly, however, embodiment researchers since the classic empiricists have argued that internal states such as meta-cognition and affect constitute sources of knowledge no less important than external experience. Recent embodiment theorists propose that knowledge acquired from introspection is central to the representation of abstract concepts (e.g., Barsalou 1999, Barsalou & Wiemer-Hastings 2005).

Finally, grounded theories are often viewed as necessarily depending on bodily states or full-blown simulations that recreate experience. Researchers in grounded cognition make neither assumption. Bodily states are not necessary for cognitive activity, although they can be closely related to it. Although simulation is a central construct, these researchers agree that simulations rarely, if ever, recreate full experiences. Instead, simulations are typically partial recreations of experience that can contain bias and error (e.g., Barsalou 1999).

THEORIES OF GROUNDED COGNITION

All grounded theories represent negative reactions to standard theories of cognition based

on amodal symbols. Additionally, grounded theories contain insights about mechanisms central to cognition that standard theories have largely ignored, such as simulation, situated action, and bodily states. Although most theories have been descriptive, they have nevertheless generated testable hypotheses addressed in empirical research. Clearly an important goal for future theory is to implement and formalize these theories.

Cognitive Linguistics Theories

Some of the first theories to champion grounded cognition in modern times arose in cognitive linguistics. These theories were negative reactions to amodal theories of syntax originating in the Cognitive Revolution (e.g., Chomsky 1957), and positive champions for the roles of bodies, situations, and simulations in language.

Lakoff & Johnson (1980, 1999) proposed that abstract concepts are grounded metaphorically in embodied and situated knowledge (also see Gibbs 1994). Specifically, these researchers argued that people possess extensive knowledge about their bodies (e.g., eating) and situations (e.g., verticality), and that abstract concepts draw on this knowledge metaphorically. For example, love can be understood as eating ("being consumed by a lover"), and affective experience can be understood as verticality ("happy is up, sad is down"). Extensive linguistic evidence across languages shows that people talk ubiquitously about abstract concepts using concrete metaphors. Such metaphors also arise extensively in literature (e.g., Turner 1996). A key issue is whether these metaphors simply reflect linguistic convention or whether they actually represent how people think (e.g., Murphy 1997). Increasing evidence suggests that these metaphors play central roles in thought (e.g., Boroditsky & Ramscar 2002, Gibbs 2006).

Other theories in cognitive linguistics have grounded the syntax and semantics of natural language in components of experience, such as paths, spatial relations, processes, and forces (e.g., Lakoff 1987; Langacker 1987, 1991; Talmy 1983, 1988). Cognitive linguists have also grounded reasoning in experience (e.g., Fauconnier 1985). Other cognitive linguists have developed grammars that use frames and constructions to capture the structure of situations (e.g., Fillmore 1985, A. Goldberg 1995). All these theories provide rich sources of hypotheses for scientific research (e.g., Coulson 2001, Kaschak & Glenberg 2000, Kemmerer 2006, Mandler 1992, Tomasello 2003).

Theories of Situated Action

These theories reflect another reaction to standard theories of cognition, again rejecting the idea that cognition revolves around computation on amodal symbols. Positively, many of these theories focus on the central roles of perception and action in cognition.

Following Gibson (1979), theories of situated action propose that the environment plays central roles in shaping cognitive mechanisms. Additionally, these theories focus on the close coupling of perception and action during goal achievement (e.g., Clark 1997, W. Prinz 1997, Thelen & L. Smith 1994, Steels & Brooks 1995), and increasingly on social interaction (e.g., Breazeal 2002). Many of these theories have originated in robotics. As a result, they are implemented computationally in robots operating in the physical world with other agents. Robotics provides a powerful test bed for developing and evaluating grounded theories of cognition that attempt to explain unified agents, not just component processes (Barsalou et al. 2007a).

Rather than adopting computational architectures that manipulate amodal symbols, theories of situated action often adopt dynamic systems as their architecture. From this perspective, fixed representations do not exist in the brain. Instead, multiple systems implement perception, action, and cognition, where each system is capable of residing in one of infinitely many continuous states. Over learning, states of these systems become coupled to

reflect patterns of interaction with each other and with the environment effective in achieving goals (attractors). Such theories have been applied to perception and action (e.g., Van Orden et al. 2005), development (e.g., Thelen et al. 2001), and cognition (e.g., Spivey 2007).

Cognitive Simulation Theories

Perceptual symbol systems. The attacks on standard theories from cognitive linguistics, situated action, dynamic systems, and elsewhere might suggest that standard theories have nothing to offer. To the contrary, Barsalou's (1999) theory of Perceptual Symbol Systems (PSS) argued that traditional approaches are correct in postulating the importance of symbolic operations for interpreting experience (Fodor & Pylyshyn 1988, Pylyshyn 1973). Although grounded theories are viewed widely as recording systems (Haugeland 1991), PSS demonstrated that grounded theories can implement symbolic functions naturally (also see Barsalou 2005a, 2007). Through the construct of simulators—corresponding roughly to concepts and types in standard theories—PSS implements the standard symbolic functions of type-token binding, inference, productivity, recursion, and propositions. This approach retains the symbolic functionality of traditional theories but implements it differently, using simulation and dynamic systems. Thus, PSS is a synthetic approach that integrates traditional theories with grounded theories.

PSS further assumes that a single, multimodal representation system in the brain supports diverse forms of simulation across different cognitive processes, including high-level perception, implicit memory, working memory, long-term memory, and conceptual knowledge. According to PSS, differences between these cognitive processes reflect differences in the mechanisms that capture multimodal states and simulate them later. In high-level perception and implicit memory, association areas in a modality capture representations (e.g., in vision) and later trigger simulations that produce perceptual completion, repetition priming, etc. Working memory utilizes the same representation system but controls it differently during simulation, using frontal mechanisms to keep a modal representation active temporarily. Long-term memory again utilizes the same representation system to simulate episodic events but controls it via medial temporal systems and different frontal areas. Finally, conceptual knowledge uses the same representational system to simulate knowledge but controls it via association areas in the temporal, parietal, and frontal lobes. According to PSS, simulation is a unifying computational principle across diverse processes in the brain, taking different forms for each. The convergence zone architecture proposed by Damasio (1989) and extended by Simmons & Barsalou (2003) offers one way to implement a single representation system controlled by multiple simulation mechanisms.

Barsalou (2003) integrated PSS with situated cognition, proposing that simulations typically contextualize the categories that they represent in background situations, which include objects, agents, actions, events, and mental states (also see Yeh & Barsalou 2006). Barsalou et al. (2003) similarly proposed that situated simulations explain embodiment effects in social psychology through a pattern-completion inference mechanism.

In humans, the simulation system central to PSS is closely integrated with the linguistic system. Paivio (1971, 1986) developed an account of how language and simulation interact—Dual Code Theory—and amassed considerable evidence for it. Glaser (1992) and Barsalou and colleagues (2007b) offered revisions of this theory that place deep conceptual processing in the simulation system, not in the linguistic system. Barsalou (2005b) further proposed that nonhumans have roughly the same simulation system as humans but lack a linguistic system to control it. Barsalou (2007) proposed that humans' powerful symbolic capabilities emerge from interactions between language and simulation.

Memory theories. Glenberg (1997) argued that traditional accounts of memory focus too much on the passive storage of information and too little on the importance of situated action. Glenberg proposed that memory primarily serves to control situated action, and that the patterns stored in memory reflect the nature of bodily actions and their ability to mesh with situations during goal pursuit. Drawing on Gibson (1979), Glenberg suggested that the perception of relevant objects triggers affordances for action stored in memory. Conversely, reasoning about future actions relies on remembering affordances while suppressing perception of the environment (Glenberg et al. 1998).

Rubin (2006) argued that traditional accounts of memory are limited by only attempting to explain simple laboratory paradigms. When richer forms of memory are considered, such as autobiographical memory and oral history, more complex theories are required. Rubin proposed Basic Systems Theory as an account of complex memory phenomena. Similar to PSS and its situated extensions, Basic Systems Theory proposes that a complex memory contains many multimodal components from vision, audition, action, space, affect, language, etc., and that retrieving a memory involves simulating its multimodal components together. Conway (1990, 2002) similarly stressed the centrality of multimodal representations in autobiographical memory.

Social Simulation Theories

Simulation plays increasingly important roles in theories of social cognition (Goldman 2006). Of particular interest is explaining how we represent the mental states of other people. Simulation theories propose that we represent other people's minds using simulations of our own minds. To feel someone else's pain, we simulate our own pain.

Mirror neuron circuits typically underlie social simulation theories. In primates, a subset of the neural circuit used to manipulate objects becomes active when perceiving another agent perform an action to achieve a goal (Rizzolatti & Craighero 2004). To recognize and understand another agent's action, primates simulate the perceived action in their own motor system. Notably, mirror neurons within these circuits respond strongest to the goal of the action, not to the action itself. Thus, mirror circuits help perceivers infer an actor's intention, not simply recognize the action performed.

More generally, social neuroscientists propose that mirror circuits provide a general mechanism for understanding diverse mental states in others (e.g., Decety & Grèzes 2006, Gallese et al. 2004, 2007). To understand how someone else feels when disgusted, we simulate how we feel when disgusted. From this perspective, simulation provides a general mechanism for establishing empathy. Simulation theorists further propose that simulation supports other important social processes, such as imitation and social coordination. Some simulation theorists propose that mirror circuits contributed to the evolution of human language (Arbib 2005, Rizzolatti & Arbib 1998).

EMPIRICAL EVIDENCE

Surprisingly little research has attempted to test the widely accepted assumption that amodal symbols represent knowledge. Indeed, hardly any research before the past ten years attempted to assess directly the format in which knowledge is represented (e.g., amodal symbols, simulation). Furthermore, relatively little research assessed other aspects of the grounded view, such as the roles of situations and bodily states in cognition. During the past ten years, however, many researchers have designed experiments to assess grounded theories explicitly. The results of these experiments increasingly suggest that simulations, situations, and bodily states play central roles in cognition. Because of space limitations, many important findings are not cited.

Perception and Action

Perceptual inference. The simulation process central to accounts of grounded cognition plays ubiquitous roles in perception. During perception, states of perceptual systems become stored in memory (e.g., for vision and audition). Similar stimuli perceived later trigger these memories, simulating the perceptual states they contain. As these simulations become active, they produce perceptual inferences that go beyond perceived stimuli in useful ways.

Goldstone (1995) taught people simple associations between a shape (e.g., square) and a color (e.g., dark red). Later, when a colored shape was flashed (e.g., a red square), and participants had to reproduce its color, they distorted the color towards the prototypical color associated with the shape seen earlier. Perceiving the object's shape activated a simulation of its prototypical color, which then distorted perception of the current color. Hansen et al. (2006) similarly showed that simulations of an object's natural color (e.g., yellow for banana) distort achromatic perception of the object (e.g., a gray banana) toward the opponent color (e.g., a bluish banana).

During the perception of motion, visual simulations similarly arise that go beyond the physical motion present. In motion continuation, viewers simulate the visual trajectory of an object beyond its actual trajectory, falsely remembering anticipated motion (e.g., Freyd 1987). Knowledge about whether an object moves quickly or slowly affects the perceived speed of these simulated trajectories (e.g., Reed & Vinson 1996). During apparent motion, simulations of possible human action similarly shape perception of interpolated motion (e.g., Shiffrar & Freyd 1990, 1993). Stevens et al. (2000) showed that simulations in the motor system underlie these inferences. Analogous simulations produce somatosensory anticipations of an object tracing a trajectory over the body (Blankenburg et al. 2006).

Lexical knowledge produces simulations that contribute to speech perception. In the phoneme restoration effect, listeners use auditory knowledge about a word to simulate a missing phoneme (e.g., Warren 1970). Samuel (1997) showed that these simulations utilize early auditory systems.

Perception-action coordination. As people perceive visual objects, simulations of potential actions become active in preparation for situated action. Tucker & Ellis (1998) showed that the perceived handle of a cup activates a grasping simulation that inadvertently affects motor responses on an unrelated task. Tucker & Ellis (2001) showed that viewing an object grasped with a precision or power grip (e.g., a grape versus a hammer) produces a simulation of the appropriate action. Symes et al. (2007) showed that these simulations are sensitive to whether an object's orientation makes it easily graspable. Glover et al. (2004) showed that the size of an object affects these simulations. Bub et al. (2007) showed that a perceived object (or object name) automatically triggers simulations of both grasping and functional actions. Tucker & Ellis (2004) also showed that these simulations occur when the name of an object is read (e.g., "grape"). Helbig et al. (2006) showed that action simulations speed visual recognition of objects on which these actions are performed. Using fMRI, Chao & Martin (2000) showed that perceived objects activate the brain's grasping circuit (see Lewis 2006 for a review).

Researchers increasingly extend these original findings in creative ways. In Bosbach et al. (2005), accurately judging the weight of an object lifted by another agent requires simulating the lifting action in one's own motor and somatosensory systems. In Repp & Knoblich (2004), a pianist's ability to identify auditory recordings of his or her own playing depends on simulating the motor actions underlying it. In Pulvermüller et al. (2006), hearing a word activates the articulatory actions associated with producing it. In Proffitt (2006), simulations of perceived effort affect visual perception (but not action-guided

movement). Being tired from a run makes a hill look steeper. Carrying a heavy pack makes a path look longer.

Motor simulations are also central to basic motor control. As a simple action is performed, the motor system constructs a feedforward simulation of the action to guide and correct it (e.g., Grush 2004, Wolpert et al. 1999). These motor simulations also play roles in generating visual inferences about the anticipated actions of perceived agents (Wilson & Knoblich 2005).

Perception of space. Rather than being isotropic, the perception of space is shaped by the body, the body's relation to the environment, and the body's potential for action (Franklin & Tversky 1990). Locating objects along the vertical axis of the body is easiest because of the body's perceived asymmetry with respect to the ground. Locating objects along the front-back axis is next easiest because of the potential for action to the front. Locating objects along the left-right axis is most difficult because environmental and bodily cues are lacking. Longo & Laurenco (2007) found that people's perception of near space extends further outward as their arm length increases, suggesting that individual differences in bodies produce individual differences in space perception.

Memory

Implicit memory. Implicit memory appears closely related to perceptual inference. In both, perceptual memories become active and affect perception. As described above, simulations during perceptual inference create perceptions that go beyond stimulus information. In implicit memory, simulations increase perceptual fluency and the likelihood that perceptions are categorized correctly (i.e., repetition priming). If, for example, a perceived face activates an implicit memory, the face may be perceived more quickly and accurately.

Several general findings support the conclusion that implicit memory results from the simulation of perceptual memories (Roediger & McDermott 1993, Schacter et al. 2004). First, perceptual processing is typically important for establishing robust implicit learning, suggesting that perceptual memories are responsible (e.g., Jacoby 1983). Second, repetition priming is strongest when the modalities of the memory and the perceived stimulus match, for example, when an auditory memory exists to help process an auditory stimulus (e.g., Kirsner et al. 1989). Third, repetition priming is strongest when perceptual details of the memory and perceived stimulus match, such as orientation, size, font, etc. (e.g., Jacoby & Hayman 1987, Jolicoeur 1985). Fourth, imagining a stimulus produces repetition priming similar to actually perceiving it, suggesting that shared perceptual representations underlie both (e.g., Roediger & Blaxton 1987, Schacter & Graf 1989). For all these reasons, the simulation of perceptual states appears central to implicit memory.

Explicit memory. Similar to implicit memory, conscious memory of previous episodes relies heavily on modal representations. Extensive reviews of supporting findings can be found in Paivio (1971, 1986), Conway (1990, 2002), and Rubin (2006), who build theories of explicit memory from this evidence. In general, these theories assume that multimodal simulations of previous episodes are central to episodic recollection. Simulation also appears central to constructing future events based on memories of past events (Schacter & Addis 2007).

Although particularly strong evidence for multimodal simulation comes from research on autobiographical memory, even simple laboratory experiments demonstrate simulation. Consider experiments that manipulate whether words are studied visually or auditorally (e.g., Wheeler et al. 2000). When retrieval of these words is tested later in a scanner, visual areas become active following visual study, whereas auditory areas become active following auditory study. Thus, the retrieval of a word simulates the modal

operations performed at encoding. Buckner & Wheeler (2001) review many such findings.

Within a single modality, the distributed brain states associated with studying different kinds of stimuli are simulated later at retrieval. Polyn et al. (2005) found that the distributed neural pattern associated with studying faces later reappeared when remembering them, as did the patterns for studying locations or objects. Kent & Lamberts (2006) similarly found that the speed of processing different perceptual dimensions at encoding was linearly related to the speed of processing them at retrieval.

Simulation also provides a natural explanation of various memory effects. Because a stimulus leaves memories in the modal areas that encoded it, greater activation in modal areas occurs when remembering something that actually occurred than when falsely remembering something that did not (Slotnick & Schacter 2004). Remembering a stimulus specifically produces greater activation in modal areas than remembering it generally (Garoff et al. 2005). Simulating a scene at encoding that extends the boundary of a studied picture produces reconstructive error later at retrieval (e.g., Intraub et al. 1998). Reinstating actions at retrieval performed earlier during encoding facilitates memory (Ross et al. 2007).

Working memory. Neuroscience research with nonhumans established the distributed neural circuits that store an absent stimulus in working memory (e.g., Levy & Goldman-Rakic 2000). To maintain a working memory, neurons in the frontal lobes maintain a simulation of the absent stimulus in the modal system that processed it originally. More specifically, different regions of frontal cortex maintain working memories for different types of modal content. For example, some regions maintain working memories of objects, whereas others maintain working memories of spatial locations. Even more specifically, different populations of frontal neurons are highly selective for the specific features they maintain (Pasternak & Greenlee 2005). For example, different frontal populations maintain working memories for motion in different directions, for textures of different spatial frequency, etc.

Research on imagery has further established the central role of modal simulation in working memory. Considerable behavioral evidence indicates that visual imagery in working memory simulates visual processing (e.g., Finke 1989, Kosslyn 1980, Shepard & Cooper 1982). Neural evidence strongly corroborates this conclusion (e.g., Kosslyn et al. 2000). Analogously, motor imagery simulates motor processing (e.g., Grèzes & Decety 2001, Jeannerod 1995), and auditory imagery simulates auditory processing (e.g., Halpern et al. 2004).

When action is relevant to visual imagery, the motor system becomes engaged, consistent with theories of situated action. For example, when visual rotation of a body part is imagined, bodily constraints shape the rotational trajectory (e.g., Parsons 1987a,b). Similarly, mental rotation of visual objects is accompanied by motor simulations of making them turn (e.g., Richter et al. 2000).

Knowledge and Conceptual Processing

Although simulation in working memory has been accepted for many years, simulation as the basis of knowledge representation is still considered a radical proposal. Nevertheless, considerable evidence now demonstrates the presence of simulation during conceptual processing.

Behavioral evidence. Researchers have used the property verification task to assess whether conceptual processing utilizes simulation. On each trial, the word for a category is presented (e.g., HORSE) followed by a word for a property that is either true or false of the category (e.g., mane versus horns). According to standard theories, participants assess relations between amodal symbols for concepts

and properties to verify properties. According to grounded views, participants simulate the concept and the property and then assess whether the simulated property can be found in the simulated concept.

Consistent with the simulation view, Solomon & Barsalou (2004) found that perceptual variables such as size best predicted verification times and errors. As properties became larger, verifying them became more difficult, consistent with the finding that verifying properties perceptually becomes more difficult as properties become larger (cf. Morrison & Tversky 1997). Solomon & Barsalou (2001) similarly found that property representations contain detailed perceptual information, difficult to verbalize, suggesting that participants simulated properties to verify them. Borghi et al. (2004) found that the positions of properties in space are simulated during their verification.

If participants simulate properties to verify them, then having to switch from one modality to another while simulating properties should incur a switching cost, analogous to the cost of switching attention from one modality to another in perception (e.g., Spence et al. 2000). Pecher at al. (2003, 2004) found support for this hypothesis, as did Marques (2006) and Vermeulen et al. (2007).

Lesion evidence. Neuropsychologists have reported that lesions in a particular modality increase the likelihood of losing categories that rely on it for processing a category (e.g., Cree & McRae 2003, Damasio & Damasio 1994, Gainotti 2006, Gainotti et al. 1995, Humphreys & Forde 2001, Simmons & Barsalou 2003, Warrington & McCarthy 1987, Warrington & Shallice 1984). For example, damage to visual areas increases the likelihood of losing animals because visual processing is often the dominant modality for interacting with this category. Conversely, damage to motor areas increases the likelihood of losing the tools category, because motor processing is often the dominant modality. Similarly, damage to color processing areas can produce deficits in color knowledge (e.g., Miceli et al. 2001), and damage to spatial processing areas can produce deficits in location knowledge (e.g., Levine et al. 1985). Additional research demonstrates that other mechanisms beside modal representations contribute to category-specific deficits (e.g., Caramazza & Shelton 1998, Cree & McRae 2003, Simmons & Barsalou 2003, Tyler et al. 2000).

Neuroimaging evidence. Neuroimaging research further confirms that simulation plays a central role in conceptual processing (Martin 2001, 2007). When conceptual knowledge about objects is represented, brain areas that represent their properties during perception and action become active. In particular, brain areas that represent the shape and color of objects (fusiform gyrus), the motion they exhibit (middle and superior temporal lobe), and the actions that agents perform on them (premotor and parietal areas) become active to represent these properties conceptually. When people perform the property verification task described above, modal areas for the properties tested become active, including brain areas for shape, color, size, sound, taste, action, and touch (e.g., R. Goldberg et al. 2006, Kan et al. 2003, Kellenbach et al. 2001, Simmons et al. 2007).

Further evidence comes from different profiles of multimodal activation for different categories. When people process animals conceptually, visual areas are especially active; when people process artifacts, motor areas become active (e.g., Kiefer 2005; Martin 2001, 2007; Thompson-Schill 2003). Similarly, when people process foods conceptually, gustatory areas become active (e.g., Simmons et al. 2005). When people process things that smell, olfactory areas become active (e.g., Gonzalez et al. 2006). Additionally, the property areas just noted are often segregated by category (Martin 2007). Within the motion processing system, for example, distinct areas represent motion conceptually for animals versus artifacts.

Language Comprehension

Situation models. Although the presence of modal representations in such a high-level cognitive task as comprehension might seem implausible, supporting evidence has existed for decades. Early work on comprehension inferences strongly suggested the presence of spatial representations (e.g., Bransford & Johnson 1973). Bower & Morrow (1990) found that people represent text meaning with situation models that have spatial properties (also see Glenberg et al. 1987, Rinck & Bower 2004). Other research has shown that readers take spatial perspectives on scenes described in texts (e.g., Black et al. 1979, Spivey et al. 2000). Intraub & Hoffman (1992) found that readers confused pictures with texts, suggesting that readers simulated text meaning. Gernsbacher et al. (1990) found that individual abilities for comprehending events visually versus verbally were highly correlated, suggesting that modal representations underlie both. Potter et al. (1986) showed that replacing words with pictures did not disrupt sentence processing, suggesting that the pictures were integrated effortlessly into modal representations of sentence meaning (also see Glaser 1992).

Perceptual simulation. More recently, researchers have addressed the role of perceptual simulation in representing texts. In much research reviewed by Zwaan & Madden (2005), participants read a sentence and then processed a picture that either matched or mismatched something implied but not stated literally. For example, participants read "The ranger saw the eagle in the sky" and then named a subsequent picture of an eagle either with its wings outstretched or folded. If readers constructed simulations to represent sentences, these simulations should have contained implicit perceptual information such as object shape. Consistent with this prediction, participants were faster to name the eagle with outstretched wings. Many experiments have demonstrated these matching effects, consistent with the simulation view.

In another line of research, participants maintained irrelevant information in working memory while processing sentences about scenes (Fincher-Kiefer 2001, Fincher-Kiefer & D'Agostino 2004). Drawing predictive spatial inferences about the described scenes was worse when working memory contained interfering visual information than when it contained noninterfering verbal information, suggesting that readers represented the texts with simulations.

Motor simulation. Many researchers have demonstrated the presence of motor simulations in comprehension. Across several lines of research, Pulvermüller (2005) found that when participants simply read the word for an action, the motor system becomes active to represent its meaning. More specifically, verbs for head, arm, and leg actions produce head, arm, and leg simulations in the respective areas of the motor system. These simulations become active quickly, within a few hundred milliseconds, as illustrated by magnetoencephalography (MEG). These simulations also play causal roles in lexical processing, given that transcranial magnetic stimulation (TMS) over the relevant motor areas affects behavioral performance (e.g., Buccino et al. 2005, Pulvermüller et al. 2005). Myung et al. (2006) similarly showed that motor simulations triggered by words produce priming across lexical decision trials.

Many other researchers have assessed whether physical actions affect comprehension. Klatzky et al. (1989) showed that priming a motor action affected the time to judge the sensibility of a simple phrase describing an action. Similarly, comprehension is facilitated when the action to make a response is consistent with text meaning (Glenberg & Kaschak 2003) and also when the action to control text presentation is consistent (Zwaan & Taylor 2006). When reading about a sport, such as hockey, experts produce motor simulations absent in novices (Holt & Beilock 2006).

Other research shows that participants simulate motion through space as they read texts. Richardson et al. (2003) found that readers simulate horizontal and vertical paths implied by both concrete and abstract verbs (e.g., push versus lift, argue versus respect). Matlock (2004) found that implied fictive motion (e.g., the road runs through the valley) produces corresponding simulations of motion through space. Richardson & Matlock (2007) found that these simulations produce related eye movements. Meier & Robinson (2004) found that reading positively valenced words orients attention up, whereas reading negatively valenced words orients attention down. Schubert (2005) similarly found that reading words associated with high versus low power orients attention up versus down, respectively. Meier & Robinson (2006) found that depression increases downward orientation.

Affective simulation. Researchers have also shown that people simulate affective states during comprehension. When people read taboo words and reprimands, affective reactions, as measured by skin conductance, are stronger when read in a first language than in a second language acquired at a later age (Harris et al. 2003). Because greater affect is associated with these expressions at younger ages, native language speakers continue to simulate these affective responses when reading them as adults.

A reader's affective state interacts with the affective content of a text. In Havas et al. (2007), participants' faces were configured discretely into states associated with particular emotions prior to judging the sensibility of sentences that contained emotional content. When facial emotion matched sentence emotion, comprehension was better than when they mismatched. Embodied states of the face triggered emotional states, which in turn interacted with sentence comprehension. Barrett (2006) suggests that affective simulation underlies the conceptualization of emotion that occurs in comprehension and other processes.

Gesture. Another important form of embodiment in language is the gesture that spontaneously accompanies speech (McNeill 2005). Producing gestures helps speakers retrieve words whose meanings are related to the gestures (e.g., Krauss 1998). Speakers also produce gestures to help listeners comprehend what they say (e.g., Alibali et al. 2001, Kelly 2001, Valenzeno et al. 2003). In child development, gesture can convey an emerging conceptualization that cannot yet be articulated in speech (e.g., Goldin-Meadow 2003). Kelly et al. (2002) integrate gesture with grounded theories of language.

Thought

Physical reasoning. Much work shows that simulations play central roles in reasoning about physical situations (Hegarty 2004). When people view a static configuration of gears, for example, they use simulation to infer the direction in which a particular gear will turn. People similarly use simulation to draw inferences about how a configuration of pulleys will work or when water will spill from a tipped glass.

Numerous sources of evidence support the use of simulation in these tasks. The time to draw an inference is often correlated with the duration of a physical event, such as how long a gear takes to turn (e.g., Schwartz & Black 1996). Drawing inferences often produces associated gestures (e.g., Hegarty et al. 2005). Carrying out associated actions can improve inference (e.g., Schwartz 1999). When working memory is filled with visuospatial information, inferences suffer compared with when working memory is filled with verbal information (e.g., Sims & Hegarty 1997). Individual differences in spatial ability correlate with the ability to draw inferences (e.g., Hegarty & Steinhoff 1997). Hegarty (2004) concludes that spatial simulation, not visual imagery, plays the central role in reasoning about physical situations. Furthermore, the simulations that underlie this reasoning appear piecemeal and sketchy, not holistic and detailed.

Abstract reasoning. Abstract forms of reasoning have not received as much attention as physical reasoning. Although Johnson-Laird's (1983) mental model theory could be made compatible with grounded views, the mental models in his theory typically contain amodal symbols, not simulations. Much circumstantial evidence, however, suggests that simulation plays central roles in abstract reasoning. For example, philosophers of science observe frequently that scientific and mathematical discoveries typically arise from simulation (e.g., Barwise & Etchemendy 1991, Hadamard 1949, Nersessian 1999). Widespread content effects in reasoning similarly implicate simulations and situations in abstract reasoning (e.g., Cheng & Holyoak 1985).

Further evidence that abstract reasoning is grounded comes from research inspired by metaphor theory. When people reason about the abstract concept of time, they use space metaphorically to draw inferences (e.g., Boroditsky 2000, Boroditsky & Ramscar 2002). For example, when people hear, "Next Wednesday's meeting has been moved forward two days," their inference about whether the new meeting day is Monday or Friday depends on their current spatial trajectory. Similarly, how people conceptualize time reflects whether their language describes space horizontally or vertically (Boroditsky 2001).

Social Cognition

Embodiment effects. Social psychologists have reported embodiment effects for decades (Barsalou et al. 2003, Niedenthal et al. 2005). Bodily states can be effects of social cognition. For example, activating the elderly stereotype causes people to walk slowly and to perform lexical decision slowly (e.g., Dijksterhuis & Bargh 2001). Similarly, seeing an in-group member engages the smiling musculature (e.g., Vanman et al. 1997).

Bodily states are not simply effects of social cognition; they also cause it. When a facial expression or posture is adopted, it elicits associated mental states. For example, engaging the smiling musculature produces positive affect (e.g., Strack et al. 1988), whereas slumping produces negative affect (e.g., Stepper & Strack 1993). Actions produce similar outcomes. Nodding one's head produces positive affect (e.g., Wells & Petty 1980), whereas pushing away with the arms produces negative affect (e.g., Cacioppo et al. 1993).

Barsalou et al. (2003) proposed that these embodiment effects reflect a pattern-completion inference mechanism that supports situated action. According to this view, representations of familiar situations that contain embodiments become established in memory (e.g., receiving a gift, feeling positive affect, and smiling). When part of this situation occurs (e.g., receiving a gift), it activates the remainder of the situational pattern, producing associated embodiments (e.g., smiling). Similarly, if smiling is engaged, it activates representations of situations that contain it, producing associated pattern components (e.g., positive affect, generosity). E. Smith & Semin (2004) review much further evidence that situated action organizes social cognition. Barsalou et al. (2005) examine embodiment in religious cognition.

Social mirroring. Accumulating evidence implicates simulation in many social processes (Decety & Grèzes 2006, Gallese et al. 2004, Goldman 2006, Iacoboni 2007, Rizzolatti & Craighero 2004). In general, mirror circuits appear to underlie these simulations, establishing empathy between perceivers and perceived actors. Using mirror circuits, perceivers infer the goals of others (e.g., Kohler et al. 2002) and infer their affective states, such as pain and disgust (e.g., Jackson et al. 2005, Wicker et al. 2003). Mirror circuits underlie a variety of other social activities, including imitation (e.g., Iacoboni et al. 1999) and social coordination (e.g., Sebanz et al. 2006).

In general, a mirror circuit does not provide a complete account of a social activity but contributes to a larger system. For example, additional brain areas beyond mirror circuits

prevent perceivers from confusing someone else's mental state with their own (Decety & Grèzes 2006). In imitation, simulating how the imitation of an action will look and feel is also important (Iacoboni et al. 1999). Joint attention and timing are also central in social coordination (Sebanz et al. 2006).

Individual differences in simulation ability produce individual differences in social cognition. For example, individual differences in the ability to simulate other people's mental states, such as pain, correlate with rated empathy (e.g., Jackson et al. 2005). Individual differences in expertise, such as ballet, correlate with the ability to mirror relevant action (Calvo-Merino et al. 2005).

Development

Newborn infants imitate the facial expressions and bodily movements of adults, simulating the actions that they see physically (Meltzoff & Moore 1983). As infants grow older, they understand the perceived actions of others in terms of what they have come to understand about their own actions and intentions (Meltzoff 2007). Once infants experience the occluding effects of a blindfold, for example, they understand that an adult wearing a blindfold cannot see. Thus, mirroring plays a central role in development, as infants use simulations of their own experience to understand the goals and actions of others.

Researchers increasingly demonstrate that development depends critically on bodily states (e.g., L. Smith 2005b) and situated action (e.g., L. Smith & Gasser 2005). For example, L. Smith et al. (1999) showed that the development of object permanence is not simply a cognitive achievement (as long believed) but also a grounded one. Specifically, motor perseveration plays a major role in tasks that measure object permanence. Longo & Bertenthal (2006) similarly showed that motor simulations contribute to perseveration.

Other developmental tasks also exhibit strong dependence on action. For example, the motor actions performed while learning a category influence the visual features abstracted into its representation (L. Smith 2005a). Similarly, the actions performed on objects during play later cause children to place the objects in spatial clusters that reflect shared categories (Namy et al. 1997). In general, extensive amounts of learning occur between perception, action, and cognition as development progresses (e.g., Greco et al. 1990, Rochat & Striano 1999).

THEORETICAL AND EMPIRICAL ISSUES

Grounded cognition in its modern form is sufficiently new and controversial that many issues surround it. A sample of these issues follows.

Does the Brain Contain Amodal Symbols?

Researchers who once denied that the modalities had anything to do with cognition now acknowledge their potential relevance. The empirical evidence that the modalities have something to do with cognition has become compelling. Nevertheless, most researchers in cognitive psychology and cognitive science are not ready to completely abandon traditional theories. One widely held view is that simulations in the modalities play peripheral roles in cognition, while classic operations on amodal symbols still play the central roles.

It will be important for future research to assess this mixed view. Can empirical evidence be found for the amodal symbols still believed by many to lie at the heart of cognition? As mentioned above, surprisingly few attempts have been made to establish empirical support for amodal symbols. If amodal symbols are to remain central in cognitive theories, empirical support is necessary. It will not be enough to rely on the fact that theories built from amodal symbols can mimic cognitive abilities. It will also be important to demonstrate that computation on amodal symbols constitutes the underlying mechanism.

Furthermore, modal symbols must be localized in the brain, and neural principles for processing them explained.

Does Simulation Implement Classic Symbolic Operations?

Conversely, can simulation mechanisms be shown to be more than merely peripheral to cognition? Can simulation implement the core cognitive functions that many researchers still believe require amodal symbols? As described above, grounded theories, such as PSS and cognitive linguistics grammars, have illustrated how simulation mechanisms can implement, in principle, core cognitive functions, including type-token binding, inference, productivity, recursion, and propositions. The existence of these operations in the cognitive system is not in question. How the brain actually implements them is. Amodal formalisms for symbolic operations may provide a theoretical shorthand for expressing what the brain computes, but simulation, or something else, may be the mechanism that actually implements these operations.

Clearly, computational implementations are required to demonstrate convincingly that simulation can implement symbolic operations. Empirical evidence will be required to support these accounts. If future research succeeds in these projects, the viability of amodal symbols as plausible cognitive constructs may increasingly come into question.

Are Simulations and Embodiments Causal or Epiphenomenal?

Proponents of amodal views often suggest that amodal symbols play the central causal roles in cognitive computation, with simulations and embodiments simply being epiphenomenal. Establishing whether simulations and embodiments play causal roles is indeed an important issue. Considerable evidence exists already, however, that they do. For example, TMS over motor areas affects linguistic processing (e.g., Buccino et al. 2005, Pulvermüller et al. 2005). If simulations in motor areas are epiphenomenal, then modulating brain activity in these areas should have no effect on the causal sequence of processes underlying language, but it does. Similarly, experimentally manipulated bodily states, assigned randomly to participants, produce extensive effects throughout social cognition (Barsalou et al. 2003), situated action (e.g., Tucker & Ellis 1998, 2001, 2004), and linguistic processing (e.g., Glenberg & Kaschak 2003). If these bodily states are epiphenomenal, they should have no effect on the causal sequence of processes underlying behavioral performance, but again they do.

Conversely, it is essential for proponents of amodal views to demonstrate that amodal symbols play causal roles in cognition (assuming that evidence for their existence in the brain can be found). Consider neuroimaging studies that find activations in modal areas during conceptual processing (e.g., Martin 2007). If these activations are epiphenomenal, then it is essential to identify alternative amodal brain areas that play the causal role in producing conceptual performance. Interestingly, many of these studies fail to find significant activations outside modal areas, suggesting that amodal processes do not contribute to conceptual processing, and that the active modal areas observed play the causal roles, given that they are the only areas active.

Assessing the causal roles of simulations and embodiments clearly requires much further research. Nevertheless, significant evidence exists already that they are not epiphenomenal.

What Roles Do Statistical Representations Play?

Research inspired by neural networks and Bayesian statistics has clearly shown that the brain is exquisitely sensitive to the statistical structure of experience. Interestingly, these two approaches often (but not always) assume

that statistical processing occurs in a modular system separate from the brain's modal systems, much like traditional symbolic theories. In other words, these approaches have remained relatively ungrounded.

By no means is this necessary. To the contrary, statistical processing is central to grounded cognition, as illustrated by dynamic systems approaches. Similarly, theories such as PSS assume that neural networks underlie the convergence zone architecture that implements simulation. Furthermore, Bayesian statistics can be viewed as statistical accounts of the multimodal information stored in the dynamic systems that generate simulations and guide situated action. Depending on the particular distribution of multimodal content captured for a category, the Bayesian statistics describing it will vary, as will the simulations and situated actions generated from it. Bayesian theories provide a powerful tool for describing the content and behavior of these systems.

How Is Language Grounded?

Language provides an excellent domain in which to combine symbolic operations, statistical processing, and grounding. Symbolic operations are clearly central to linguistic processing. Thematic roles of verbs are bound to values (e.g., binding the instrument role for "eat" to spoon). Open-class words for nouns, modifiers, and verbs, and adverbs combine productively to form novel phrasal and sentential structures (e.g., combining different color modifiers with different object head nouns to form noun phrases such as red hair, blond hair, and red wine). Phrasal structures embed recursively (e.g., "The dog the cat chased howled"). Propositions extracted from linguistic utterances represent meaning beyond surface structure [e.g., extracting chase (cat, dog) from either "The cat chased the dog" or the "The dog was chased by the cat"].

Statistical processing is also central to language use. Much research shows that statistical distributions of word senses contribute to ambiguity resolution during syntactic analysis (e.g., Trueswell 1996). Similarly, statistical distributions of argument structures and their instantiations contribute to sentence processing (e.g., McRae et al. 2005).

Finally, grounding is also central to comprehension, as we saw earlier. As people comprehend a text, they construct simulations to represent its perceptual, motor, and affective content. Simulations appear central to the representation of meaning.

Thus, language use is a domain where the study of symbolic operations, statistical processing, and grounding can be integrated. Numerous issues challenge the integration of these perspectives. Do amodal symbols or simulation mechanisms implement the symbolic operations that underlie linguistic processing? As sentences are processed incrementally, are simulations constructed incrementally to reflect the semantic contribution of each incoming word? Does the compositional structure of syntax correspond to the compositional structure of simulations? Do language statistics affect the specific simulations constructed during comprehension? Do cognitive linguistics grammars offer useful frameworks for integrating symbolic operations, statistical processing, and grounding?

Does the Brain Contain a Single Representational System?

As described above, some simulation theories propose that a single multimodal representation system underlies diverse cognitive processes, including top-down perception, implicit memory, working memory, explicit memory, and conceptual knowledge. According to this view, simulation is a unifying computational principle throughout the brain, with different control systems operating on a shared representational system to produce different forms of simulation in different processes.

Is this proposal correct? If so, what is the nature of the shared representational system? Within a given modality, is the

representational system organized hierarchically, as appears to be the case in the visual and motor systems? If so, do some processes access these hierarchical representations at higher or lower levels than others? For example, explicit memory, conceptual processing, and language might tend to access high-level representations, whereas top-down perception, implicit memory, and working memory might tend to access lower-level representations. Another central issue concerns the different control mechanisms for different processes. Where are they located in the brain, and why do they reside in these particular locations? How do differences between them implement different processes?

How Does the Brain Represent Abstract Concepts?

Abstract concepts pose a classic challenge for grounded cognition. How can theories that focus on modal simulations explain concepts that do not appear modal? This concern often reflects the misperception described above that conceptual content in grounded theories can only come from perception of the external world. Because people perceive internal states, however, conceptual content can come from internal sources as well. Preliminary evidence suggests that introspective information is indeed central to the representation of abstract concepts (e.g., Barsalou & Wiemer-Hastings 2005, Wiemer-Hastings et al. 2001). Such findings suggest that we need to learn much more about how people perceive and conceptualize internal states. Notably, people simulate internal states similar to how they simulate external states (e.g., Havas et al. 2007, Niedenthal et al. 2005). Thus, simulations of internal states could provide much of the conceptual content central to abstract concepts (Barsalou 1999).

Abstract concepts also appear to depend heavily on situations and situated action (Schwanenflugel 1991). Processing an abstract concept by itself is difficult but becomes much easier when a background situation contextualizes it. Barsalou & Wiemer-Hastings (2005) report evidence for extensive situational content in abstract concepts.

Because the scientific study of concepts has primarily focused so far on concrete concepts, we actually know remarkably little about abstract concepts, even from the perspective of traditional cognitive theories. Nevertheless, abstract concepts appear to play central roles throughout human cognition, especially in meta-cognition, social interaction, education, industry, and social institutions. Regardless of whether simulations of introspections and situations underlie the representation of abstract concepts, much more effort should be devoted to understanding them.

Do Mirror Neuron Systems Pervade Social Cognition?

Much excitement surrounds the discovery of mirror neuron systems. As described above, social simulation theories propose that these systems underlie many important social phenomena. One central issue is assessing whether mirror systems do indeed play all these roles, and perhaps others. If so, then why do humans exhibit such different social abilities than nonhuman primates who also have mirror systems? What other systems contribute to these differences? Also, to what extent do compromised mirror systems underlie psychopathologies associated with a lack of intersubjectivity, such as autism and schizophrenia (e.g., Gallese 2003)?

METHODOLOGICAL ISSUES

Besides addressing theoretical and empirical issues, grounded cognition must address various methodological issues. Future growth and impact of this area is likely to depend on addressing these issues successfully.

Computational and Formal Theories

Grounded cognition suffers from an obvious lack of well-specified theories. Often

experiments simply attempt to demonstrate the presence of modal processing in higher cognition. Given the widespread skepticism about grounded cognition ten years ago, demonstration experiments made sense. Now that modal processing in higher cognition is becoming well documented, it is time to develop computational accounts of grounded theories, along with experiments that test them. Transitioning from demonstration experiments to analytic experiments is a natural trajectory in science, and it will undoubtedly occur in grounded cognition. This trajectory is also likely to include increasing attempts to build computational implementations, followed by formal accounts of the principles underlying them. For examples of initial attempts to implement grounded theories, see Cangelosi et al. (2000), Cangelosi & Riga (2006), Garagnani et al. (2007), Wennekers et al. (2006), and Goldreich (2007).

Integrating Disciplines and Levels of Explanation

One strength of grounded cognition is its natural fit with the brain. Because grounded cognition rests on the modalities, knowledge of how the brain implements the modalities informs grounded cognition. Furthermore, assessing neural activity in the modalities provides a natural way to test predictions of grounded theories. Clearly, however, much greater integration of cognitive and neural mechanisms must occur than the relatively simple mappings established so far. Nevertheless, the grounded approach appears to have unusual potential for integrating cognition with the brain.

Grounded cognition has significant potential to integrate other research areas as well. For example, a core principle of grounded cognition is that cognition shares mechanisms with perception, action, and introspection. Increasingly specified accounts of how cognition, perception, action, and introspection interact during situated action are likely to follow from future research. Similarly, grounded cognition has also shown potential to integrate cognitive, social, and developmental processes. Research in all three fields has increasingly incorporated simulation, situations, and bodily states as important constructs. Thus, further integration of these areas seems like another natural outcome of research in grounded cognition. As described above, robotics offers considerable potential for accomplishing this integration (Barsalou et al. 2007a).

Grounding Classic Research Paradigms

It is unlikely that grounded cognition will be fully accepted until classic research paradigms can be understood within its framework. In cognitive psychology, for example, how would a classic paradigm such as recognition memory be understood as grounded? Similarly, how might the construct of a production in a production system be understood?

One possibility is that many empirical results and their interpretations would remain roughly the same within the framework of ground cognition. Analogous to how symbolic operations can be retained in grounded views but be realized differently, well-established empirical results and explanations may often retain much of their original form. One focus of change is likely to be at the representational level. In recognition memory, for example, rather than assuming that a vector of amodal symbols represents a learning episode, its representational elements could instead be mapped into a multimodal state. At higher theoretical levels, much of the original theory might remain. Similarly, in production systems, rather than viewing the condition and action sides of a production as amodal symbols, the condition could be represented as the state of a perceptual modality, and the action could be represented as a state of the motor system. From the grounded perspective, a production is simply an association between a perception and an action. Above the

representational level, the remaining structure of a production system might again remain largely intact.

Clearly, the reinvention of classic paradigms requires careful theoretical and empirical assessment. Until grounding is integrated with classic paradigms, however, it is unlikely that it will be accepted fully. Thus, another major goal for the grounded cognition community is to illustrate how classic paradigms can be made compatible with grounding, and perhaps how grounding can take understandings of these paradigms to new levels.

ACKNOWLEDGMENT

This work was supported by National Science Foundation Grant BCS-0212134 and by DARPA contract BICA FA8650-05-C-7256 to Lawrence Barsalou.

LITERATURE CITED

Alibali MW, Heath DC, Myers HJ. 2001. Effects of visibility between speaker and listener on gesture production: Some gestures are meant to be seen. *J. Mem. Lang.* 44:169–88

Arbib MA. 2005. From monkey-like action recognition to human language: an evolutionary framework for neurolinguistics. *Behav. Brain Sci.* 28:105–67

Barrett LF. 2006. Solving the emotion paradox: categorization and the experience of emotion. *Pers. Soc. Psychol. Rev.* 10:20–46

Barsalou LW. 1999. Perceptual symbol systems. *Behav. Brain Sci.* 22:577–660

Barsalou LW. 2003. Situated simulation in the human conceptual system. *Lang. Cogn. Process.* 18:513–62

Barsalou LW. 2005a. Abstraction as dynamic interpretation in perceptual symbol systems. In *Building Object Categories*, Carnegie Sympos. Ser., ed. L Gershkoff-Stowe, D Rakison, pp. 389–431. Mahwah, NJ: Erlbaum

Barsalou LW. 2005b. Continuity of the conceptual system across species. *Trends Cogn. Sci.* 9:309–11

Barsalou LW. 2007. Grounding symbolic operations in the brain's modal systems. In *Embodied Grounding: Social, Cognitive, Affective, and Neuroscientific approaches*, ed. GR Semin, ER Smith. New York: Cambridge Univ. Press. In press

Barsalou LW, Barbey AK, Simmons WK, Santos A. 2005. Embodiment in religious knowledge. *J. Cogn. Cult.* 5:14–57

Barsalou LW, Breazeal C, Smith LB. 2007a. Cognition as coordinated noncognition. *Cogn. Process.* 8:79–91

Barsalou LW, Hale CR. 1993. Components of conceptual representation: from feature lists to recursive frames. In *Categories and Concepts: Theoretical Views and Inductive Data Analysis*, ed. I Van Mechelen, J Hampton, R Michalski, P Theuns, pp. 97–144. San Diego, CA: Academic

Barsalou LW, Niedenthal PM, Barbey A, Ruppert J. 2003. Social embodiment. In *The Psychology of Learning and Motivation*, Vol. 43, ed. B Ross, pp. 43–92. San Diego, CA: Academic

Barsalou LW, Santos A, Simmon WK, Wilson CD. 2007b. Language and simulation in conceptual processing. In *Symbols, Embodiment, and Meaning*, ed. M De Vega AM, Glenberg AC, Graesser A. Oxford: Oxford Univ. Press. In press

Barsalou LW, Wiemer-Hastings K. 2005. Situating abstract concepts. In *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thought*, ed. D Pecher, R Zwaan, pp. 129–63. New York: Cambridge Univ. Press

Barwise J, Etchemendy J. 1991. Visual information and valid reasoning. In *Visualization in Mathematics*, ed. W Zimmerman, S Cunningham, pp. 9–24. Washington, DC: Math. Assoc. Am.

Black JB, Turner TJ, Bower GH. 1979. Point of view in narrative comprehension, memory, and production. *J. Verbal Learn. Verbal Behav*. 18:187–98

Blankenburg F, Ruff CC, Deichmann R, Rees G, Driver J. 2006. The cutaneous rabbit illusion affects human primary sensory cortex somatotopically. *PLoS Biol*. 4:459–66

Borghi AM, Glenberg A, Kaschak M. 2004. Putting words in perspective. *Mem. Cogn*. 32:863–73

Boroditsky L. 2000. Metaphoric structuring: understanding time through spatial metaphors. *Cognition* 75:1–28

Boroditsky L. 2001. Does language shape thought? English and Mandarin speakers' conceptions of time. *Cogn. Psychol*. 43:1–22

Boroditsky L, Ramscar M. 2002. The roles of body and mind in abstract thought. *Psychol. Sci*. 13:185–88

Bosbach S, Cole J, Prinz W, Knoblich G. 2005. Inferring another's expectation from action: the role of peripheral sensation. *Nat. Neurosci*. 8:1295–97

Bower GH, Morrow DG. 1990. Mental models in narrative comprehension. *Science* 247:44–48

Bransford JD, Johnson MK. 1973. Considerations of some problems of comprehension. In *Visual Information Processing*, ed. WG Chase, pp. 383–438. New York: Academic

Breazeal C. 2002. *Designing Sociable Robots*. Cambridge, MA: MIT Press

Bub DN, Masson MEJ, Cree GS. 2007. Evocation of functional and volumetric gestural knowledge by objects and words. *Cognition*. In press

Buccino G, Riggio L, Melli G, Binkofski F, Gallese V, Rizzolatti G. 2005. Listening to action-related sentences modulates the activity of the motor system: a combined TMS and behavioral study. *Cogn. Brain Res*. 24:355–63

Buckner RL, Wheeler ME. 2001. The cognitive neuroscience of remembering. *Nat. Rev. Neurosci*. 2:624–34

Cacioppo JT, Priester JR, Bernston GG. 1993. Rudimentary determination of attitudes: II. Arm flexion and extension have differential effects on attitudes. *J. Personal. Soc. Psychol*. 65:5–17

Calvo-Merino B, Glaser DE, Grèzes J, Passingham RE, Haggard P. 2005. Action observation and acquired motor skills: an fMRI study with expert dancers. *Cereb. Cortex* 8:1243–49

Cangelosi A, Greco A, Harnad S. 2000. From robotic toil to symbolic theft: grounding transfer from entry-level to higher-level categories. *Connect. Sci*. 12:143–62

Cangelosi A, Riga T. 2006. An embodied model for sensorimotor grounding and grounding transfer: experiments with epigenetic robots. *Cogn. Sci*. 30:673–89

Caramazza A, Shelton JR. 1998. Domain-specific knowledge systems in the brain: the animate-inanimate distinction. *J. Cogn. Neurosci*. 10:1–34

Chao LL, Martin A. 2000. Representation of manipulable man-made objects in the dorsal stream. *Neuroimage* 12:478–84

Cheng PW, Holyoak KJ. 1985. Pragmatic reasoning schemas. *Cogn. Psychol*. 17:391–416

Chomsky N. 1957. *Syntactic Structures*. The Hague: Mouton

Clark A. 1997. *Being There: Putting Brain, Body, and World Together Again*. Cambridge, MA: MIT Press

Conway MA. 1990. *Autobiographical Memory: An Introduction*. Buckingham, UK: Buckingham Univ. Press

Conway MA. 2002. Sensory-perceptual episodic memory and its context: autobiographical memory. In *Episodic Memory: New Directions in Research*, ed. A Baddeley, JP Aggleton, MA Conway, pp. 53–70. Oxford: Oxford Univ. Press

Coulson S. 2001. *Semantic Leaps: Frame Shifting and Conceptual Blending in Meaning Construction*. New York: Cambridge Univ. Press

Cree GS, McRae K. 2003. Analyzing the factors underlying the structure and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns). *J. Exp. Psychol.: Gen*. 132:163–201

Damasio AR. 1989. Time-locked multiregional retroactivation: a systems-level proposal for the neural substrates of recall and recognition. *Cognition* 33:25–62

Damasio AR, Damasio H. 1994. Cortical systems for retrieval of concrete knowledge: the convergence zone framework. In *Large-Scale Neuronal Theories of the Brain*, ed. C Koch, JL Davis, pp. 61–74. Cambridge, MA: MIT Press

Decety J, Grèzes J. 2006. The power of simulation: imagining one's own and other's behavior. *Brain Res*. 1079:4–14

Dijksterhuis A, Bargh JA. 2001. The perception-behavior expressway: automatic effects of social perception on social behavior. In *Advances in Experimental Social Psychology*, Vol. 23, ed. MP Zanna, pp. 1–40. San Diego, CA: Academic

Epicurus (341–270 B.C.E.). 1987. Sensation, imagination, and memory. In *The Hellenistic Philosophers*, Vol. 1, ed. AA Long, DN Sedley, pp. 72–78. New York: Cambridge Univ. Press

Fauconnier G. 1985. *Mental Spaces*. Cambridge, MA: MIT Press

Fillmore CJ. 1985. Frames and the semantics of understanding. *Quad. di Semantica* 6:222–55

Fincher-Kiefer R. 2001. Perceptual components of situation models. *Mem. Cogn*. 29:336–43

Fincher-Kiefer R, D'Agostino PR. 2004. The role of visuospatial resources in generating predictive and bridging inferences. *Discourse Process*. 37:205–24

Finke RA. 1989. *Principles of Mental Imagery*. Cambridge, MA: MIT Press

Fodor JA, Pylyshyn ZW. 1988. Connectionism and cognitive architecture: a critical analysis. *Cognition* 28:3–71

Franklin N, Tversky B. 1990. Searching imagined environments. *J. Exp. Psychol.: Gen*. 119:63–76

Freyd JJ. 1987. Dynamic mental representations. *Psychol. Rev*. 94:427–38

Gainotti G. 2006. Anatomical functional and cognitive determinants of semantic memory disorders. *Neurosci. Biobehav. Rev*. 30:577–94

Gainotti G, Silveri MC, Daniele A, Giustolisi L. 1995. Neuroanatomical correlates of category-specific semantic disorders: a critical survey. *Memory* 3:247–64

Gallese V. 2003. The roots of empathy: the shared manifold hypothesis and the neural basis of intersubjectivity. *Psychopathology* 36:171–80

Gallese V, Keysers C, Rizzolatti G. 2004. A unifying view of the basis of social cognition. *Trends Cogn. Sci*. 8:396–403

Garagnani M, Wennekers T, Pulvermüller F. 2007. A neural model of the language cortex. *Neurocomputing* 70:1914–19

Garoff RJ, Slotnick SD, Schacter DL. 2005. The neural origins of specific and general memory: the role of the fusiform cortex. *Neuropsychologia* 43:847–59

Gernsbacher MA, Varner KR, Faust ME. 1990. Investigating differences in general comprehension skill. *J. Exp. Psychol.: Learn. Mem. Cogn*. 16:430–45

Gibbs RW Jr. 1994. *The Poetics of Mind: Figurative Thought, Language, and Understanding*. New York: Cambridge Univ. Press

Gibbs RW Jr. 2006. *Embodiment and Cognitive Science*. New York: Cambridge Univ. Press
Gibson JJ. 1979. *The Ecological Approach to Visual Perception*. New York: Houghton Mifflin
Glaser WR. 1992. Picture naming. *Cognition* 42:61–105
Glenberg AM. 1997. What memory is for. *Behav. Brain Sci*. 20:1–55
Glenberg AM, Kaschak MP. 2003. The body's contribution to language. In *The Psychology of Learning and Motivation*, Vol. 43, ed. B Ross, pp. 93–126. New York: Academic
Glenberg AM, Meyer M, Lindem K. 1987. Mental models contribute to foregrounding during text comprehension. *J. Mem. Lang*. 26:69–83
Glenberg AM, Schroeder JL, Robertson DA. 1998. Averting the gaze disengages the environment and facilitates remembering. *Mem. Cogn*. 26:651–58
Glover S, Rosenbaum DA, Graham J, Dixon P. 2004. Grasping the meaning of words. *Exp. Brain Res*. 154:103–8
Goldberg A. 1995. *Constructions. A Construction Grammar Approach to Argument Structure*. Chicago: Univ. Chicago Press
Goldberg RF, Perfetti CF, Schneider W. 2006. Perceptual knowledge retrieval activates sensory brain regions. *J. Neurosci*. 26:4917–21
Goldin-Meadow S. 2003. *Hearing Gesture: How Our Hands Help Us Think*. Cambridge, MA: Harvard Univ. Press
Goldman A. 2006. *Simulating Minds: The Philosophy, Psychology, and Neuroscience of Mindreading*. Oxford: Oxford Univ. Press
Goldreich D. 2007. A Bayesian perceptual model replicates the cutaneous rabbit and other tactile spatiotemporal illusions. *PLoS ONE* 2:e333
Goldstone RL. 1995. Effects of categorization on color perception. *Psychol. Sci*. 5:298–304
Gonzalez J, Barros-Loscertales A, Pulvermüller F, Meseguer V, Sanjuán A, et al. 2006. Reading cinnamon activates olfactory brain regions. *Neuroimage* 32:906–12
Greco C, Hayne H, Rovee-Collier C. 1990. Roles of function, reminding, and variability in categorization by 3-month-old infants. *J. Exp. Psychol.: Learn. Mem. Cogn*. 16:617–33
Grèzes J, Decety J. 2001. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Hum. Brain Mapp*. 12:1–19
Grush R. 2004. The emulation theory of representation: motor control, imagery, and perception. *Behav. Brain Sci*. 27:377–442
Hadamard J. 1949. *The Psychology of Invention in the Mathematical Field*. New York: Dover
Halpern AR, Zatorre RJ, Bouffard M, Johnson JA. 2004. Behavioral and neural correlates of perceived and imagined timbre. *Neuropsychologia* 42:1281–92
Hansen T, Olkkonen M, Walter S, Gegenfurtner KR. 2006. Memory modulates color appearance. *Nat. Neurosci*. 9:1367–68
Harnad S. 1990. The symbol grounding problem. *Physica D* 42:335–46
Harris CL, Aycicegi A, Berko Gleason J. 2003. Taboo words and reprimands elicit greater autonomic reactivity in a first than in a second language. *Appl. Linguistics* 24:561–79
Haugeland J. 1991. Representational genera. In *Philosophy and Connectionist Theory*, ed. W Ramsey, SP Stitch, DE Rumelhart, pp. 61–89. Hillsdale, NJ: Erlbaum
Havas DA, Glenberg AM, Rinck M. 2007. Emotion simulation during language comprehension. *Psychon. Bull. Rev*. In press
Hegarty M. 2004. Mechanical reasoning as mental simulation. *Trends Cogn. Sci*. 8:280–85
Hegarty M, Mayer S, Kriz S, Keehner M. 2005. The role of gestures in mental animation. *Spat. Cogn. Comput*. 5:333–56
Hegarty M, Steinhoff K. 1997. Use of diagrams as external memory in a mechanical reasoning task. *Learn. Individid. Differ*. 9:19–42

Helbig HB, Graf M, Kiefer M. 2006. The role of action representations in visual object recognition. *Exp. Brain Res*. 174:221–28

Holt LE, Beilock SL. 2006. Expertise and its embodiment: examining the impact of sensorimotor skill expertise on the representation of action-related text. *Psychon. Bull. Rev*. 13:694–701

Humphreys GW, Forde EME. 2001. Hierarchies, similarity, and interactivity in object recognition: "category-specific" neuropsychological deficits. *Behav. Brain Sci*. 24:453–509

Iacoboni M. 2007. Understanding others: imitation, language, empathy. In *Perspectives on Imitation: From Cognitive Neuroscience to Social Science*, ed. S Hurley, N Chater. Cambridge, MA: MIT Press. In press

Iacoboni M, Woods RP, Brass M, Bekkering H, Mazziotta JC, Rizzolatti G. 1999. Cortical mechanisms of human imitation. *Science* 286:2526–28

Intraub H, Gottesman CV, Bills AJ. 1998. Effects of perceiving and imagining scenes on memory for pictures. *J. Exp. Psychol.: Learn. Mem. Cogn*. 24:186–201

Intraub H, Hoffman JE. 1992. Reading and visual memory: remembering scenes that were never seen. *Am. J. Psychol*. 105:101–14

Jackson PL, Meltzoff AN, Decety J. 2005. How do we perceive the pain of others: a window into the neural processes involved in empathy. *NeuroImage* 24:771–79

Jacoby L. 1983. Remembering the data: analyzing interactive processes in reading. *J. Verbal Learn. Verbal Behav*. 22:485–508

Jacoby LL, Hayman CAG. 1987. Specific visual transfer in word identification. *J. Exp. Psychol.: Learn. Mem. Cogn*. 13:456–63

Jeannerod M. 1995. Mental imagery in the motor context. *Neuropsychologia* 33:1419–32

Johnson-Laird PN. 1983. *Mental Models*. Cambridge, MA: Harvard Univ. Press

Jolicoeur P. 1985. The time to name disoriented natural objects. *Mem. Cogn*. 13:289–303

Kan IP, Barsalou LW, Solomon KO, Minor JK, Thompson-Schill SL. 2003. Role of mental imagery in a property verification task: fMRI evidence for perceptual representations of conceptual knowledge. *Cogn. Neuropsychol*. 20:525–40

Kant E. 1787/1965. *The Critique of Pure Reason*. Transl. NK Smith. New York: St. Martin's Press

Kaschak MP. Glenberg AM. 2000. Constructing meaning: the role of affordances and grammatical constructions in sentence comprehension. *J. Mem. Lang*. 43:508–29

Kellenbach ML, Brett M, Patterson K. 2001. Large, colorful, or noisy? Attribute- and modal activations during retrieval of perceptual attribute knowledge. *Cogn. Affect. Behav. Neurosci*. 1:207–21

Kelly SD. 2001. Broadening the units of analysis in communication: speech and nonverbal behaviours in pragmatic comprehension. *J. Child Lang*. 28:325–49

Kelly SD, Iverson J, Terranova J, Niego J, Hopkins M, Goldsmith L. 2002. Putting language back in the body: speech and gesture on three timeframes. *Dev. Neuropsychol*. 22:323–49

Kemmerer D. 2006. The semantics of space: integrating linguistic typology and cognitive neuroscience. *Neuropsychologia* 44:1607–21

Kent C, Lamberts K. 2006. Modeling the time course of feature perception and feature information retrieval. *J. Mem. Lang*. 55:553–71

Kiefer M. 2005. Repetition priming modulates category-related effects on event-related potentials: further evidence for multiple cortical semantic systems. *J. Cogn. Neurosci*. 17:199–211

Kirsner K, Dunn JC, Standen P. 1989. Domain-specific resources in word recognition. In *Implicit Memory: Theoretical Views*, ed. S Lewandowsky, JC Dunn, K Kirsner, pp. 99–122. Hillsdale, NJ: Erlbaum

Klatzky RL, Pelligrino JW, McCloskey BP, Doherty S. 1989. The role of motor representations in semantic sensibility judgments. *J. Mem. Lang.* 28:56–77

Kohler E, Keysers Cl, Umiltá MA, Fogassi L, Gallese V, Rizzolatti G. 2002. Hearing sounds, understanding actions: action representation in mirror neurons. *Science* 297:846–48

Kosslyn SM. 1980. *Image and Mind*. Cambridge, MA: Harvard Univ. Press

Kosslyn SM. 1994. *Image and Brain*. Cambridge, MA: MIT Press

Kosslyn SM, Ganis G, Thompson WL. 2000. Neural foundations of imagery. *Nat. Rev. Neurosci.* 2:635–42

Kosslyn SM, Thompson WL, Ganis G. 2006. *The Case for Mental Imagery*. Oxford: Oxford Univ. Press

Krauss RM. 1998. Why do we gesture when we speak? *Curr. Dir. Psychol. Sci.* 7:54–59

Lakoff G. 1987. *Women, Fire, and Dangerous Things: What Categories Reveal About the Mind*. Chicago: Univ. Chicago Press

Lakoff G, Johnson M. 1980. *Metaphors We Live By*. Chicago: Univ. Chicago Press

Lakoff G, Johnson M. 1999. *Philosophy in the Flesh: The Embodied Mind and Its Challenge to Western Thought*. New York: Basic Books

Langacker RW. 1987. *Foundations of Cognitive Grammar: Vol. 1. Theoretical Prerequisites*. Stanford, CA: Stanford Univ. Press

Langacker RW. 1991. *Foundations of Cognitive Grammar, Vol. II: Descriptive Application*. Stanford, CA: Stanford Univ. Press

Lewis JW. 2006. Cortical networks related to human use of tools. *Neuroscientist* 12:211–31

Levine DN, Warach J, Farah MJ. 1985. Two visual systems in mental imagery: dissociation of "what" and "where" in imagery disorders due to bilateral posterior cerebral lesions. *Neurology* 35:1010–18

Levy R, Goldman-Rakic PS. 2000. Segregation of working memory functions within the dorsolateral prefrontal cortex. *Exp. Brain Res.* 133:23–32

Longo MR, Bertenthal BI. 2006. Common coding of observation and execution of action in 9-month-old infants. *Infancy* 10:43–59

Longo MR, Laurenco SF. 2007. Space perception and body morphology: extent of near space scales with arm length. *Exp. Brain Res.* 177:285–90

Mandler M. 1992. How to build a baby: II. Conceptual primitives. *Psychol. Rev.* 99:587–604

Marques JF. 2006. Specialization and semantic organization: evidence for multiple semantics linked to sensory modalities. *Mem. Cogn.* 34:60–67

Martin A. 2001. Functional neuroimaging of semantic memory. In *Handbook of Functional Neuroimaging of Cognition*, ed. R Cabeza, A Kingstone, pp. 153–86. Cambridge, MA: MIT Press

Martin A. 2007. The representation of object concepts in the brain. *Annu. Rev. Psychol.* 58:25–45

Matlock T. 2004. Fictive motion as cognitive simulation. *Mem. Cogn.* 32:1389–400

McNeill D. 2005. *Gesture and Thought*. Chicago: Univ. Chicago Press

McRae K, Hare M, Elman JL, Ferretti TR. 2005. A basis for generating expectancies for verbs from nouns. *Mem. Cogn.* 33:1174–84

Meier BP, Robinson MD. 2004. Why the sunny side is up: associations between affect and vertical position. *Psychol. Sci.* 15:243–47

Meier BP, Robinson MD. 2006. Does "feeling down" mean seeing down? Depressive symptoms and vertical selective attention. *J. Res. Personal.* 40:451–61

Meltzoff AN. 2007. "Like me": a foundation for social cognition. *Dev. Sci.* 10:126–34

Meltzoff AN, Moore MK. 1983. Newborn infants imitate adult facial gestures. *Child Dev.* 54:702–9

Miceli G, Fouch E, Capasso R, Shelton JR, Tomaiuolo F, Caramazza A. 2001. The dissociation of color from form and function knowledge. *Nat. Neurosci*. 4:662–67

Morrison JB, Tversky B. 1997. Body schemas. In *Proceedings of the Cognitive Science Society*, ed. MG Shafto, P Langley, pp. 525–29. Mahwah, NJ: Erlbaum

Murphy GL. 1997. Reasons to doubt the present evidence for metaphoric representation. *Cognition* 62:99–108

Myung J, Blumstein SE, Sedivy JC. 2006. Playing on the typewriter, typing on the piano: manipulation knowledge of objects. *Cognition* 98:223–43

Namy LL, Smith LB, Gershkoff-Stowe L. 1997. Young children discovery of spatial classification. *Cogn. Dev*. 12:163–84

Nersessian NJ. 1999. Model-based reasoning in conceptual change. In *Model-Based Reasoning in Scientific Discovery*, ed. L Magnani, NJ Nersessian, P Thagard, pp. 5–22. New York: Kluwer Acad./Plenum

Niedenthal PM, Barsalou LW, Winkielman P, Krauth-Gruber S, Ric F. 2005. Embodiment in attitudes, social perception, and emotion. *Pers. Soc. Psychol. Rev*. 9:184–211

Paivio A. 1971. *Imagery and Verbal Processes*. New York: Holt, Rinehart & Winston

Paivio A. 1986. *Mental Representations: A Dual Coding Approach*. New York: Oxford Univ. Press

Parsons LM. 1987a. Imagined spatial transformations of one's body. *J. Exp. Psychol.: Gen*. 116:172–91

Parsons LM. 1987b. Imagined spatial transformations of one's hands and feet. *Cogn. Psychol*. 19:178–241

Pasternak T, Greenlee MW. 2005. Working memory in primate sensory systems. *Nat. Rev. Neurosci*. 6:97–107

Pecher D, Zeelenberg R, Barsalou LW. 2003. Verifying properties from different modalities for concepts produces switching costs. *Psychol. Sci*. 14:119–24

Pecher D, Zeelenberg R, Barsalou LW. 2004. Sensorimotor simulations underlie conceptual representations: modality-specific effects of prior activation. *Psychon. Bull. Rev*. 11:164–67

Polyn SM, Natu VS, Cohen JD, Norman KA. 2005. Category-specific cortical activity precedes retrieval memory search. *Science* 310:1963–66

Potter MC, Kroll JF, Yachzel B, Carpenter E, Sherman J. 1986. Pictures in sentences: understanding without words. *J. Exp. Psychol.: Gen*. 115:281–94

Prinz J. 2002. *Furnishing the Mind: Concepts and Their Perceptual Basis*. Cambridge, MA: MIT

Prinz W. 1997. Perception and action planning. *Eur. J. Cogn. Psychol*. 9:129–54

Proffitt DR. 2006. Embodied perception and the economy of action. *Perspect. Psychol. Sci*. 1:110–22

Pulvermüller F. 2005. Brain mechanisms linking language and action. *Nat. Rev. Neurosci*. 6:576–82

Pulvermüller F, Hauk O, Nikulin VV, Ilmoniemi RJ. 2005. Functional links between motor and language systems. *Eur. J. Neurosci*. 21:793–97

Pulvermüller F, Huss H, Kherif F, Martin FMP, Hauk O, Shtyrov Y. 2006. Motor cortex maps articulatory features of speech sounds. *Proc. Natl. Acad. Sci. USA* 103:7865–70

Pylyshyn ZW. 1973. What the mind's eye tells the mind's brain: a critique of mental imagery. *Psychol. Bull*. 80:1–24

Reed CL, Vinson NG. 1996. Conceptual effects on representational momentum. *J. Exp. Psychol.: Hum. Percept. Perform*. 22:839–50

Reid T. 1785/1969. *Essays on the Intellectual Powers of Man*. Cambridge, MA: MIT Press

Repp BH, Knoblich G. 2004. Perceiving action identity: how pianists recognize their own performances. *Psychol. Sci*. 15:604–9

Richardson DC, Matlock T. 2007. The integration of figurative language and static depictions: an eye movement study of fictive motion. *Cognition* 102:129–38

Richardson DC, Spivey MJ, Barsalou LW, McRae K. 2003. Spatial representations activated during real-time comprehension of verbs. *Cogn. Sci*. 27:767–80

Richter W, Somorjai R, Summers R, Jarmasz M, Menon RS, et al. 2000. Motor area activity during mental rotation studied by time-resolved single-trial fMRI. *J. Cogn. Neurosci*. 12:310–20

Rinck M, Bower GH. 2004. Goal-based accessibility of entities within situation models. In *The Psychology of Learning and Motivation: Advances in Research and Theory*, Vol. 44, ed. BH Ross, pp. 1–33. New York: Elsevier Sci.

Rizzolatti G, Arbib MA. 1998. Language within our grasp. *Trends Neurosci*. 21:188–94

Rizzolatti G, Craighero L. 2004. The mirror-neuron system. *Annu. Rev. Neurosci*. 27:169–92

Robbins P, Aydede M, eds. 2007. *Cambridge Handbook of Situated Cognition*. New York: Cambridge Univ. Press

Rochat P, Striano T. 1999. Emerging self-exploration by 2-month-old infants. *Dev. Sci*. 2:206–18

Roediger HL, Blaxton TA. 1987. Effects of varying modality, surface features, and retention interval on priming in word fragment completion. *Mem. Cogn*. 15:379–88

Roediger HL, McDermott KB. 1993. Implicit memory in normal human subjects. In *Handbook of Neuropsychology*, Vol. 8, ed. F Boller, J Grafman, pp. 63–131. Amsterdam: Elsevier

Ross BH, Wang RF, Kramer AF, Simons DJ, Crowell JA. 2007. Action information from classification learning. *Psychon. Bull. Rev.* In press

Rubin DC. 2006. The basic-systems model of episodic memory. *Perspect. Psychol. Sci*. 1:277–311

Samuel AG. 1997. Lexical activation produces potent phonemic percepts. *Cogn. Psychol*. 32:97–127

Schacter DL, Addis DR. 2007. The cognitive neuroscience of constructive memory: remembering the past and imagining the future. *Philos. Trans. R. Soc. Lond. B Biol. Sci*. 362:773–86

Schacter DL, Dobbins IG, Schnyer DM. 2004. Specificity of priming: a cognitive neuroscience perspective. *Nat. Rev. Neurosci*. 5:853–62

Schacter DL, Graf P. 1989. Modality specificity of implicit memory for new associations. *J. Exp. Psychol.: Learn. Mem. Cogn*. 15:3–12

Schubert T. 2005. Your Highness: vertical positions as perceptual symbols of power. *J. Personal. Soc. Psychol*. 89:1–21

Schwanenflugel PJ. 1991. Why are abstract concepts hard to understand? In *The Psychology of Word Meaning*, ed. PJ Schwanenflugel, pp. 223–50. Mahwah, NJ: Erlbaum

Schwartz DL. 1999. Physical imagery: kinematic vs dynamic models. *Cogn. Psychol*. 38:433–64

Schwartz DL, Black JB. 1996. Analog imagery in mental model reasoning: depictive models. *Cogn. Psychol*. 30:154–219

Searle JR. 1980. Minds, brains, and programs. *Behav. Brain Sci*. 3:417–24

Sebanz N, Bekkering H, Knoblich G. 2006. Joint action: bodies and minds moving together. *Trends Cogn. Sci*. 10:70–76

Shepard RN, Cooper LA. 1982. *Mental Images and Their Transformations*. New York: Cambridge Univ. Press

Shiffrar M, Freyd JJ. 1990. Apparent motion of the human body. *Psychol. Sci*. 4:257–64

Shiffrar M, Freyd JJ. 1993. Timing and apparent motion path choice with human body photographs. *Psychol. Sci*. 6:379–84

Simmons WK, Barsalou LW. 2003. The similarity-in-topography principle: reconciling theories of conceptual deficits. *Cogn. Neuropsychol*. 20:451–86

Simmons WK, Martin A, Barsalou LW. 2005. Pictures of appetizing foods activate gustatory cortices for taste and reward. *Cereb. Cortex* 15:1602–8

Simmons WK, Ramjee V, Beauchamp MS, McRae K, Martin A, Barsalou LW. 2007. Common neural substrates for perceiving and knowing about color and action. *Neuropsychologia* 45:2802–10

Sims VK, Hegarty M. 1997. Mental animation in the visual-spatial sketchpad: evidence from dual-task studies. *Mem. Cogn*. 25:321–32

Slotnick SD, Schacter DL. 2004. A sensory signature that distinguishes true from false memories. *Nat. Neurosci*. 7:664–72

Smith ER, Semin GR. 2004. Socially situated cognition: cognition in its social context. *Adv. Exp. Soc. Psychol*. 36:53–117

Smith LB. 2005a. Action alters shape categories. *Cogn. Sci*. 29:665–79

Smith LB. 2005b. Cognition as a dynamic system: principles from embodiment. *Dev. Rev*. 25:278–98

Smith LB, Gasser M. 2005. The development of embodied cognition: six lessons from babies. *Artif. Life* 11:13–30

Smith LB, Thelen E, Titzer R, McLin D. 1999. Knowing in the context of acting: the task dynamics of the A-not-B Error. *Psychol. Rev*. 106:235–60

Solomon KO, Barsalou LW. 2001. Representing properties locally. *Cogn. Psychol*. 43:129–69

Solomon KO, Barsalou LW. 2004. Perceptual simulation in property verification. *Mem. Cogn*. 32:244–59

Spence C, Nicholls MER, Driver J. 2000. The cost of expecting events in the wrong sensory modality. *Percept. Psychophys*. 63:330–36

Spivey M. 2007. *The Continuity of Mind*. New York: Oxford Univ. Press

Spivey M, Tyler M, Richardson D, Young E. 2000. Eye movements during comprehension of spoken scene descriptions. *Proc. 22nd Annu. Conf. Cogn. Sci. Soc.*, pp. 487–92. Mahwah, NJ: Erlbaum

Steels L, Brooks R. 1995. *The Artificial Life Route to Artificial Intelligence: Building Embodied Situated Agents*. Mahwah, NJ: Erlbaum

Stepper S, Strack F. 1993. Proprioceptive determinants of emotional and nonemotional feelings. *J. Personal. Soc. Psychol*. 64:211–20

Stevens JA, Fonlupt P, Shiffrar M, Decety J. 2000. New aspects of motion perception: selective neural encoding of apparent human movements. *NeuroReport* 11:109–15

Strack F, Martin LL, Stepper S. 1988. Inhibiting and facilitating conditions of the human smile: a nonobtrusive test of the facial feedback hypothesis. *J. Personal. Soc. Psychol*. 54:768–77

Symes E, Ellis R, Tucker M. 2007. Visual object affordances: object orientation. *Acta Psychol*. 124:238–55

Talmy L. 1983. How language structures space. In *Spatial Orientation: Theory, Research, and Application*, ed. H Pick, L Acredelo, pp. 225–82. New York: Plenum

Talmy L. 1988. Force dynamics in language and cognition. *Cogn. Sci*. 12:49–100

Thelen E, Schoner G, Scheier C, Smith LB. 2001. The dynamics of embodiment: a field theory of infant perseverative reaching. *Behav. Brain Sci*. 24:1–86

Thelen E, Smith LB. 1994. *A Dynamic Systems Approach to the Development of Cognition and Action*. Cambridge, MA: MIT Press

Thompson-Schill SL. 2003. Neuroimaging studies of semantic memory: inferring "how" from "where." *Neuropsychologia* 41:280–92

Tomasello M. 2003. *Constructing a Language: A Usage-Based Theory of Language Acquisition*. Cambridge, MA: Harvard Univ. Press

Trueswell JC. 1996. The role of lexical frequency in syntactic ambiguity resolution. *J. Mem. Lang.* 35:566–85
Tucker M, Ellis R. 1998. On the relations between seen objects and components of potential actions. *J. Exp. Psychol.: Hum. Percept. Perform.* 24:830–46
Tucker M, Ellis R. 2001. The potentiation of grasp types during visual object categorization. *Visual Cogn.* 8:769–800
Tucker M, Ellis R. 2004. Action priming by briefly presented objects. *Acta Psychol.* 116:185–203
Turner M. 1996. *The Literary Mind*. New York: Oxford Univ. Press
Tyler LK, Moss HE, Durrant-Peatfield MR, Levy JP. 2000. Conceptual structure and the structure of concepts: a distributed account of category-specific deficits. *Brain Lang.* 75:195–231
Valenzeno L, Alibali MW, Klatzky RL. 2003. Teachers' gestures facilitate students' learning: a lesson in symmetry. *Contemp. Educ. Psychol.* 28:187–204
Van Orden GC, Holden JG, Turvey MT. 2005. Human cognition and 1/f scaling. *J. Exp. Psychol.: Gen.* 134:117–23
Vanman EJ, Paul BY, Ito TA, Miller N. 1997. The modern face of prejudice and structural features that moderate the effect of cooperation on affect. *J. Personal. Soc. Psychol.* 73:941–59
Vermeulen N, Niedenthal PM, Luminet O. 2007. Switching between sensory and affective systems incurs processing costs. *Cogn. Sci.* In press
Warren RM. 1970. Perceptual restoration of missing speech sounds. *Science* 167:392–93
Warrington EK, McCarthy RA. 1987. Categories of knowledge: further fractionations and an attempted integration. *Brain* 110:1273–96
Warrington EK, Shallice T. 1984. Category specific semantic impairments. *Brain* 107:829–54
Watson JB. 1913. Psychology as the behaviorist sees it. *Psychol. Rev.* 20:158–77
Wells GL, Petty RE. 1980. The effects of overt head movements on persuasion: compatibility and incompatibility of responses. *Basic Appl. Soc. Psychol.* 1:219–30
Wennekers T, Garagnani M, Pulvermüller F. 2006. Language models based on Hebbian cell assemblies. *J. Physiol. Paris* 100:16–30
Wheeler ME, Petersen SE, Buckner RL. 2000. Memory's echo: vivid remembering reactivates sensory-specific cortex. *Proc. Natl. Acad. Sci. USA* 97:11125–29
Wicker B, et al. 2003. Both of us disgusted in my insula: the common neural basis of seeing and feeling disgust. *Neuron* 40:655–64
Wiemer-Hastings K, Krug J, Xu X. 2001. Imagery, context availability, contextual constraint, and abstractness. *Proc. 23rd Annu. Conf. Cogn. Sci. Soc.*, pp. 1134–39. Mahwah, NJ: Erlbaum
Wilson M. 2002. Six views of embodied cognition. *Psychon. Bull. Rev.* 9:625–36
Wilson M, Knoblich G. 2005. The case for motor involvement in perceiving conspecifics. *Psychol. Bull.* 131:460–73
Wolpert DM, Ghahramani Z, Jordan MI. 1999. An internal model for sensorimotor integration. *Science* 269:1880–82
Yeh W, Barsalou LW. 2006. The situated nature of concepts. *Am. J. Psychol.* 119:349–84
Zwaan RA, Madden CJ. 2005. Embodied sentence comprehension. In *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thought*, ed. D Pecher, R Zwaan, pp. 224–45. New York: Cambridge Univ. Press
Zwaan RA, Taylor LJ. 2006. Seeing, acting, understanding: motor resonance in language comprehension. *J. Exp. Psychol.: Gen.* 135:1–11

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